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USING LARGE WIND POWER PLANTS TO DIRECTLY DRIVE SYNCHRONOUS GENERATORS IN PARALLEL OPERATION WITH A GOVERNING NETWORK

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16. Abstract

Various aspects of wind-powered synchronous generators are described. The influence of the fan-wheel characteristic on damping of transients is slight. Altering vane position is the only feasible method for regulating power in order to avoid overloading the generator. In designing the fan-wheel, and choosing the number of vanes, the operating behavior of the generator and the danger of resonance must be considered ahead of efficiency. Practical operating characteristics of the fan-wheel must be known to the electrical engineer if he is to calculate the course of events during a transient.

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5. Numerical Example /388*

a. Influence on Damping and the Time Constant

In order to get an idea of the order of magnitude of the influence of the fan-wheel characteristic curve on the damping of the oscillation, we again assume the conditions of the previously treated plan.

We have already mentioned that in order to illustrate the effects more clearly, an exaggeratedly large value of σ_n (namely, about $\sigma_n = 0.38$) was assumed for the damping torque curve in Fig. 3. For our generator, we should have used $\sigma_n = 0.05$, so that the line DBF would be much steeper than in Fig. 3. Hence, it can immediately be recognized that the effect of the characteristic curve will be quite small.

Numerically, we obtain $\tau_1 = 1.03$ for the assumed characteristic curve at the intercept A_1. Thus, $\sigma_n/\tau_1 = 0.05/1.03 = 0.0485$. Thus, in the event of a sudden overload of $(1 + \varepsilon) = 1.34$ (point C), the reinforcement of the damping will be $\xi = 1 + 1.34 \cdot 0.0485 = 1.065$.

Furthermore, we now obtain from Eq. (23):

$$T_{ed} = \frac{T_e}{\sqrt{1-(1{,}065 \cdot 0{,}104)^2}} = \frac{T_e}{0{,}993}$$

The difference between T_{ed} and T_e is thus negligibly small in

*Numbers in the margins indicate pagination in the foreign text.

this case as well.

In accordance with Eq. (25), the time constant of decay will now be smaller by a factor of 1/1.065, i.e.

$$T = 1.70/1.065 = 1.60 \text{ sec}$$

The greatest amplitude in the first forward oscillation will now be in place of Eq. (17):

$$A_h = A_0 e^{-\pi \xi \delta} = A_0 e^{-0{,}348} = 0{,}706\, A_0,$$

i.e. only a bit smaller than without consideration of the slope of the characteristic curve.

For the case in which C coincides with K_1, the previously computed values hold without correction.

We now investigate the situation when the point C lies to the left of the pullout point. Since pushing the load point very far to the left of the pullout point will be avoided on principle, it can be assumed that the characteristic curve will not be any steeper in this case than on the right side of the curve. Rather, the tangent at the new load point will be flatter, i.e. will have a larger value for τ_1 than on the right branch.

We assume that the rated load was placed at the pullout point K (so that the abscissa 0.8 in our diagram should be replaced by 1.0, and the ordinate 1.21 likewise with 1.0). Then the new load point would be vertically above K, and the additional load would be given by $M_d/M_{d_n} = 1.43/1.21 = 1.18$ (as mentioned earlier). The intercept of the tangent would then be about $\tau_1 = -2.5$, so that $\sigma_n/\tau_1 = -0.05/2.5 = 0.02$, and $\xi =$ $= 1 - (1.18 \cdot 0.02) = 0.976$.

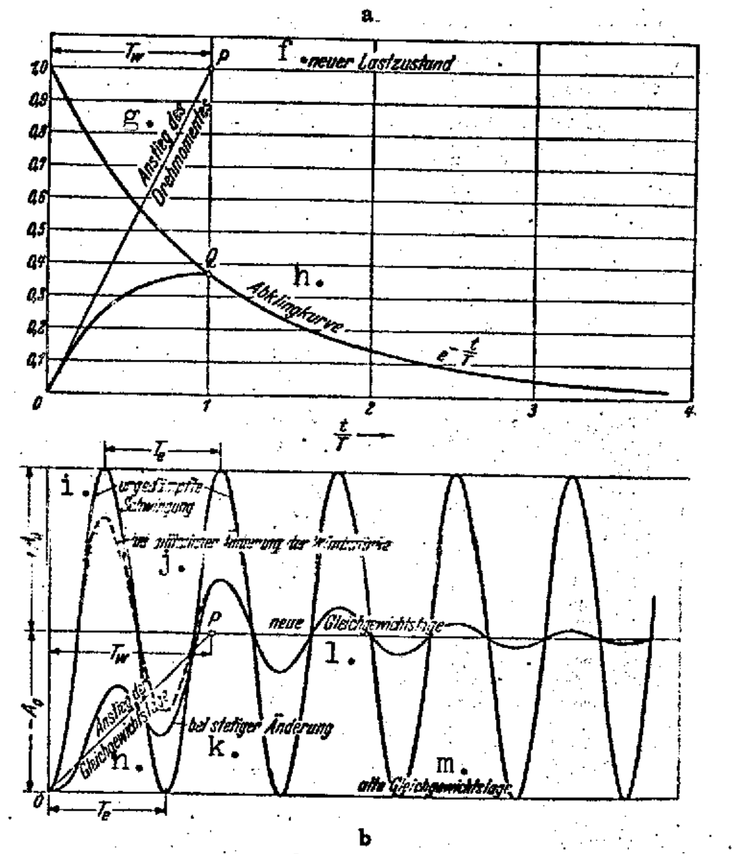

Fig. 4. Depiction of the transient.

a. Decay curve of the damped oscillation for sudden or continuous increases in torque
b. Transient toward new equilibrium position corresponding to increase in torque
T Time constant
T_e Natural period of oscillation

Key:
- f. New load level
- g. Torque rise
- h. Decay curve
- i. Undamped oscillation
- j. With sudden change in wind intensity
- k. With continuous change
- l. New equilibrium position
- m. Old equilibrium position
- n. Rise in equilibrium position

The reduction in damping is thus only 2.4%, and can thus be practically neglected. Thus there is no reason to fear that the reinforcing action of the rising characteristic curve could produce a danger of the generator falling out of synchronization.

The time constant for the decay will now be somewhat larger, namely T = 1.70/0.976 = = 1.74 sec. The transient thus lasts about 9% longer than in the transition from B to C.

However, the amplitudes of oscillation are smaller, since the increase in torque is less.

b. The Oscillation Equation and its Representation

a) The wind speed changes suddenly to a new value $v_1 = 1.10\ v_n$.

In the representation of the transient, Fig. 4a first shows the decay curve $e^{-t/T}$ with t/T as the abscissa.

In Fig. 4b, the undamped oscillation $x = -A_o \cos 2\pi t/T_e$ is first plotted with the period T_e of oscillation, which for all practical purposes can be set equal to T_{ed} in line with our earlier remarks. The oscillation begins at the negative maximum $-A_o$, i.e. at the extreme rearward position of the magnet wheel. The ordinates of this pure sine (or cosine) curve must now be multiplied by the associated ordinate of the decay curve in order to satisfy Eq. (15). In this way, we obtain the broken curve of the damped oscillation for a sudden 10% change in wind speed. The largest forward amplitude is, as previously calculated, $A_h = 0.706\ A_o$. It would thus cause an overload of the generator beyond the new equilibrium position, and in fact with $1.58\ M_{d_n}$. /389

The greatest slippage occurs at the time $t = T_e/4$ (at the first passage through the equilibrium position). From Eq. (19), it is (with $T_{ed} \approx T_e$)

$$\sigma_m = \frac{\vartheta_{s_m}}{f T_e} e^{-\frac{T_e}{4T}}$$

By Eq. (20), with the slippage changing proportionally to the torque, the greatest angular deflection (for t = 0) is

$$\frac{\vartheta_{s_m}}{\vartheta} = \frac{M_{d_1}}{M_{d_n}} - 1 = \varepsilon.$$

with T_c = 1.11 sec, T = 1.60 sec, f = 50 Hz, ε = 0.34 (for point C in Fig. 2) and $\theta = 30° = \pi/6 = 0.523$, we obtain

$$\sigma_m = \frac{0{,}34 \cdot 0{,}523}{50 \cdot 1{,}11} e^{-\frac{1{,}11}{4 \cdot 1{,}60}} = 0{,}27\ \%.$$

Thus, in the case under consideration, the maximum slippage is rather small.

b) The wind velocity changes continuously within the period T_w to the new value $v_1 = 1.10\ v_n$.

For the drawing in Fig. 4, we assume (arbitrarily) that $T_w = T$, i.e. T_w is precisely equal to the time constant of the decay curve, and in fact that not the wind velocity itself, but the torque exerted by the fan-wheel at synchronous speed (i.e. the displacement of the load point B to C), proceeds linearly with time (line OP in Fig. 4a). The equilibrium position would initially also rise linearly toward the line OP (in Fig. 4b) and then remain at constant height for the new equilibrium position.

In order to determine the oscillation ordinates, we must first multiply the ordinates of the decay curve for the period T_w by those of the rising line OP in Fig. 4a, thus obtaining the curve OQ; from point Q on, the decay curve holds as before. Now the ordinates of the curve OQ are multiplied by the ordinates of the undamped oscillation, measured from the line of the new equilibrium position. The values obtained in this way are finally deducted from the line OP of the "rise of the equilibrium position" (Fig. 4b). Thus, we obtain the heavy solid curve of the transient, which from the ordinate at point P on, is identical with the previously derived curve for a sudden change in wind intensity.

Since the increase in torque is not sudden, but takes place over a period of T = 1.6 sec, the first forward swing, which in the case of a sudden rise caused the greatest overload of the generator, is substantially diminished, so that it does not even reach the new equilibrium position. The greatest overload does not come until the second forward swing, but it only extends about 34% beyond the change in the equilibrium position, due to the damping which by now has had a marked effect. This means a temporary load on the generator of $1.452\ M_{d_n}$.

There are as yet no reliable figures on the rises in wind speed which can be anticipated in actuality. The Reichsarbeitsgemeinschaft Windkraft has concluded an agreement with the German Post Office and the German Office of Meteorology which permits the former to install automatically recording wind meters at various heights on radio towers. These records of long-term observations should then give an idea of the wind intensities, wind direction, and gusts which must be anticipated in the course of the year at the heights under consideration.

With an increasing wind rise during the time $T_w = T$, Fig. 4b shows that the largest slippage will occur at the third intersection with the continuously shifting equilibrium position, i.e. at the time $t = 5/4\ T_w$. But here we can no longer employ Eq. (19), but instead must include two corrections: first, the ordinate of the decay curve $e^{-t/T}$ must be replaced by the ordinate of the graphically determined curve OQ in Fig. 4a, i.e. 0.37. Second, to the thus determined oscillatory velocity relative to the equilibrium position, we must add the natural velocity v_g of this equilibrium position which is itself moving. Since $v_g = A_o/T$, the associated slippage is

$$\sigma_g = \frac{v_g}{v} = \frac{A_o \cdot 60}{T 2 \pi n R} = \frac{\vartheta_{s_m}}{f T 2 \pi} = \frac{0{,}178}{50 \cdot 1.60 \cdot 2\pi} = 0{,}035\,\%.$$

For the oscillation itself, $\sigma_m = \vartheta_{s_m}/(f \cdot T_e) 0.37 = 0.119\%$. Thus, the total slippage $\sigma_m + \sigma_g = 0.154\%$ in comparison with 0.27% for a sudden change in wind.

III. Regulation of Power

1. Necessity and Type of Power Regulation

However, once we have determined the transient, we have still not solved the practical problem of the wind-power drive. We have seen that, in spite of the wind wheel's characteristic tendency to adjust its rate of revolution in accordance with the wind speed, synchronous operation of an alternating-current generator is still possible. This will require that the generator runs in parallel with an alternating-current network which holds it in synchronization by setting the frequency. The fan-wheel then runs with different velocity ratios -- and thus different efficiencies -- at different wind speeds. However, this must be put up with.

In the investigation of the transient, we have further seen that the equilibrium condition for the torques of fan-wheel and generator at increased wind speed inevitably forces a higher load on the generator. This would not be serious if it were only a matter of a gust which slackened after a short period, since the generator can tolerate a certain overload for a short time without overheating. However, an overload of longer duration is not permissible for the generator due to the possibility of overheating. In addition, increases in wind intensity over the value assumed to be the normal mean will have to be anticipated in reality which are much greater than the 10% of the numerical example. This would not only result in a completely unacceptable overload on the generator due to heating, but also run the risk of falling out of synchronization.

Thus it is absolutely necessary that power be regulated as a function of wind intensity. Such a regulation cannot be performed at the generator, since the generator must work with the torque which is forced upon it by the fan-wheel.

Thus there is only one alternative: regulating power at the fan-wheel. Hence, it must be ensured that the fan-wheel delivers only the rated torque, in spite of increases in wind speed.

The regulation must therefore be mechanical. The simplest and most proven means is shifting the alignment of the vanes.

By this means, the characteristic curve found in our example in Fig. 2 and displaced upward and to the right must, by changing the angle of incidence of the vanes, be pushed down far enough so that it again passes through the fixed rated load point B. The desire to have the fan-wheel operate in the region of maximum efficiency must therefore be abandoned under certain circumstances.

In order to be able to investigate the behavior of the synchronous generator at different wind speeds with stable operation and temporary overload, the electrical engineer must therefore obtain from the aerodynamic engineer fan-wheel characteristic curves for various angles of incidence for the vanes, and not just for increased wind speeds, but also for the case /390
of reduced wind intensity, which would lower the characteristic curve and thus depress generator power if the vane alignment were not changed. The extent to which this characteristic curve can be again lifted by appropriate changes in the angle of incidence must therefore be known, i.e. the minimum wind intensity at which the full load of the generator can be obtained, likewise by abandoning the maximum efficiency of the fan-wheel.

Thus, for the operation of a wind power plant, we obtain the rule that the generator must run in the widest possible range of variable wind speed with its rated load as a base load on the network, while all load fluctuations in the network must be assumed by the other generators of the main power plant.

A special case arises when the main switch of the wind-power generator triggers, i.e. the generator load torque suddenly drops, so that the fan-wheel, and with it the magnet wheel, tries to assume the rate of revolution at the intercept. In order to keep the rise in rate of revolution within reasonable limits, the torque of the fan-wheel must likewise be reduced by shifting the positions of the vanes. Finally, power regulation through vane realignment is also required when the wind power plant is started up and synchronized with the network.

2. The Control of Regulation

The just-mentioned case of "racing" is a purely mechanical problem, since the electrical power has disappeared. The most natural method of control is therefore to use the increasing rate of revolution by means of a centrifugal governor to operate the vane-realignment mechanism.

In the loaded state of the generator, the load should be held as constant as possible as wind speed varies. However, it would not be appropriate to try to influence vane positions by a current relay, because this would then respond to an increase in the reactive current. Instead, the power delivered by the generator would have to be used as the control quantity, and the relay would have to be constructed on a wattmeter basis. In order to be able, if needed, to adjust the load of the generator to another value, the response value of the wattmeter relay would likewise have to be made adjustable.

3. Influence of Vane Shifting on Transients

Figure 4 showed how the magnet wheel moves in a damped oscillation to a new lead position corresponding to the new load state when the wind intensity increases by 10%. The purpose of shifting the vanes is now to re-establish the original equilibrium position corresponding to the rated load. Of course, this does not take place suddenly, but requires a certain period of time. The actual process of vane realignment depends on the moment of inertia of the vanes relative to twisting, and on the intensity of the twisting forces, and would therefore have to be given

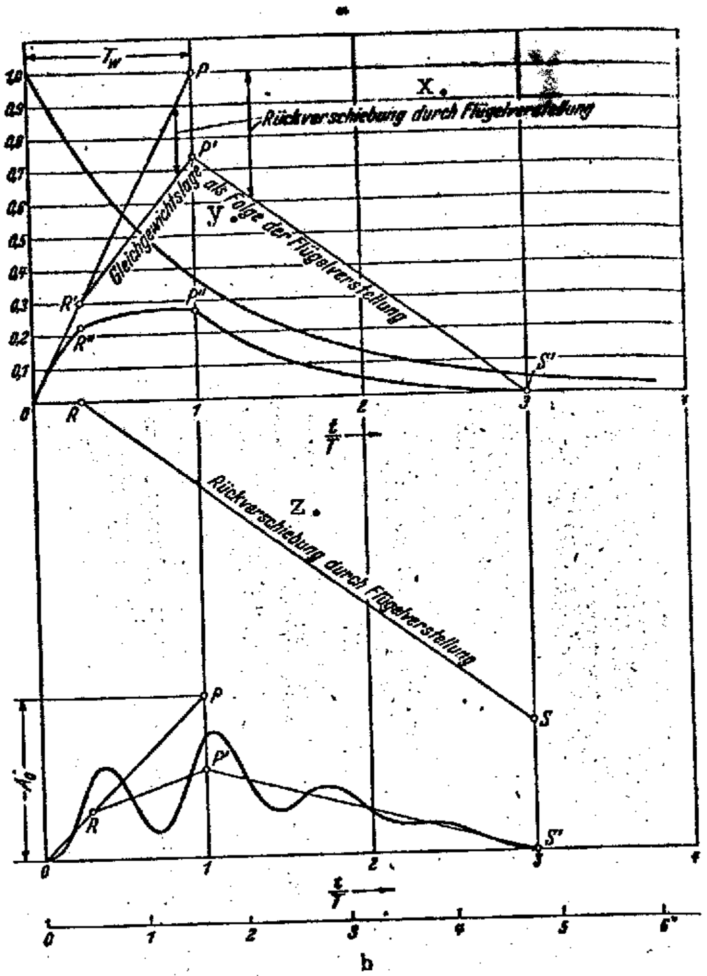

Fig. 5. Influence of vane shifting.

a. Decay curve with continuous rise in torque and simultaneous reverse displacement of the equilibrium position due to vane shifting
b. Transient with reverse displacement due to vane shifting.

Key: x. Reverse displacement due to vane shifting
y. Equilibrium position as a result of vane shifting
z. Reverse displacement due to vane shifting

to the electrical engineer by the wind-plant designer, so that the former can investigate the actual transient. Due to the lack of such figures, we can for the present only discuss the basics of this influence of vane shifting. We will do this with the aid of Figs. 5a and 5b.

In Fig. 4b, we found that, as a result of the continuous rise in torque, the equilibrium position likewise continuously shifted during the time T_W, and after T_W, from point P on, remained constant at the new value. Around this changing equilibrium position, there was then a damped oscillation, first rising, and then falling.

The realignment of the vanes now causes a continuous withdrawal of the equilibrium position back to the original value.

In order not to activate vane shifting at very small changes in wind intensity, there will be a certain delay in triggering it. Thus, the transient will continue unaffected for a short time, as depicted in Figs. 4a and 4b, for example up to the point R in Figs. 5a and 5b. Then, however, the twisting of the vanes begins, and acts to produce a withdrawal of the equilibrium position.

In the further course of events, the resulting displacement of the equilibrium position will depend on whether the forward shift due to the rise in wind speed will outweigh the reverse shift due to the twisting of the vanes, or vice versa. In Figs. 5a and 5b, the first case is assumed to hold (since it is the more unfavorable). Furthermore, due to lack of actual data, we assume that the change in equilibrium position due to vane shifting also proceeds linearly, and in fact the reverse displacement of the equilibrium position at the point S (Fig. 5a) has become just as large as the forward displacement induced by the increase in wind intensity would have been. This state should be reached after three time constants of the decay curve. The resulting behavior is given in Fig. 5a as the line OR'P'S', where the corner at P' corresponds to that at P in the original line. Now the ordinates of this line are again multiplied with those of the decay curve, OR"P"S', in Fig. 5a.

If the ordinates of this curve are now multiplied by those of the undamped oscillation (as in Fig. 4b), we again obtain the transient curve resulting from the given assumptions (Fig. 5b). Now the maximum on the second forward swing does not even reach the overload of the machine corresponding to an increase in wind intensity without vane shifting. The temporary overload of the generator would only be 26.2% (instead of 34% at point C in Fig. 2).

This investigation initially based on arbitrary assumptions /391
shows how important it is for the correct evaluation of the

transient and the resulting overloads that precise figures be obtained first on expected rises in wind intensity and second, on the amount of time required for shifting the vanes.

However, the investigations which have been conducted also show how important it is that the mechanical regulation of power operate swiftly, in order to prevent unacceptable overloads on the generator, in addition to the danger of stalling. If it is to be effective, this regulation process must therefore act within a few seconds, which ought to be directly achievable through vane shifting.

At the same time, this point also furnishes a criterion for judging the practicality of other proposals for power regulation, e.g. through turning the swivel head bearing the fan-wheel out of the wind laterally (the head must be provided in any case in order to adjust the wheel in accordance with the wind direction), or, as in a proposal of H. Honnef, by tipping the fan-wheel or even a large frame with three wind wheels. With the huge masses to be moved, the regulation process would not be able to act within a few seconds, but would instead require many minutes, probably 1/2 hour or more. Quite apart from all the mechanical difficulties which face such designs and will not be discussed here, electrical engineering considerations regarding overload and the danger of falling out of synchronization must lead to the rejection on principle of this type of regulation as thoroughly unworkable.

IV. Further Questions

1. Danger of Resonance

Resonance sufficient to cause the generator to fall out of synchronization can only occur if the drive exerts periodic jolts on the generator which are in phase with the natural oscillation frequency of the generator. Such regular jolts cannot be expected just from the wind flow itself. However, there is a possibility for resonance in the design and arrangement of the wind power plant. Since the vanes of the wheel, regardless of whether the latter is in front of or in back of the tower, will experience a decrease in the force exerted by the wind as they pass the tower, there will then be precisely periodically repeating fluctuations in torque on every revolution, corresponding to the number of vanes. For a wheel with three vanes, and n = 12 rpm, there will then be 3 · 12/60 = 0.60 jolts per second. The period of these jolts is thus

$$T_F = \frac{1}{0.60} = 1.67 \text{ sec}$$

In the investigated example, we found that the natural oscillation period was T_e = 1.11 sec. Thus there would be no danger of resonance in this case.

With a four-vaned wheel, on the other hand, one would obtain 4 · 12/60 = 0.8 jolts per second, with T_F = 1/0.80 = 1.25 sec, so that the danger of resonance would be considerably greater.

The choice of the number of vanes is thus not a question which can be decided merely on the basis of the aerodynamic criterion of most favorable exploitation of the wind. Instead, it must in the end be decided on the basis of avoiding the danger of resonance.

In order to be able to change the natural oscillation period if desired, there would in principle be two possibilities worth considering: however, one of them, namely reducing the moment of inertia, can be practically discarded at the outset. There would then remain only the second alternative: increasing the short-circuit ratio k_W, but this would be at the cost of greater material expense for the exciter winding, and poorer efficiency.

2. Does the Use of Asynchronous Generators Offer Any Advantages over Synchronous Generators?

In the introduction, we already mentioned that wind power plants have occasionally (e.g. in the Soviet Union) been designed with asynchronous generators, obviously with the idea that the rate of revolution of the asynchronous generator, which increases with the load, would be better adapted to the properties of the wind wheel than the synchronous generator, which is rigidly tied to its rate of revolution.

Whether this view is justified can easily be examined in the light of the remarks we made regarding Fig. 2. Without vane shifting, we found that a 10% increase in wind intensity displaced the intersection of the two characteristic curves from B to C, with a 34% increase in torque.

For an asynchronous generator, the characteristic curve is inclined slightly to the right, as we have seen for the damping torque. As a consequence, the intersection C moves a bit to the right, and thus also downward. An asynchronous generator of the power under consideration may be anticipated to have a rated slippage on the order of only about 2%. The characteristic curve would thus be even steeper than it was for the damping characteristic curve on which the calculation was based. Its intersection with the characteristic curve of the fan-wheel would then have an ordinate of 1.305. The benefit relative to overload of 1.34 for the synchronous generator would thus be only 3.5%, which is hardly a significant advantage.

Of course, the overload of the generator could be reduced by installing in the rotor circuit a "slip resistor," which, at the rated power of the stator, would force a higher rate of revolution on the rotor in accordance with that of the fan-wheel, thus twisting the characteristic curve of the generator to the right. But this would drastically reduce the efficiency of the generator. One would then have to get even more power from the wind at the increased rate of revolution than at rated operation, but this extra power would then be converted to heat in the slip resistor, and thus be uselessly dissipated.

Furthermore, the asynchronous generator can also only operate in parallel with a network fed by synchronous generators, which supply it with the frequency and the magnetizing current. It is just this which is a further drawback of the asynchronous generator. In view of the large diameters under consideration, the air gap must be made considerably larger for reasons of operating reliability than would normally be called for by the relatively small pole pitch. However, this means an extraordinary increase in the magnetizing current to be delivered by the network, and thus a very poor cos ϕ. While the synchronous generator can be called on to deliver reactive current to the network, and thus relieve the other generators in their reactive current delivery, the asynchronous generator will increase the amount of reactive current to be delivered by the other generators, and thus correspondingly will have a detrimental effect on the cos ϕ of the entire network. Even here, there would still have to be a mechanical control using vane shifting to adapt to the variability in wind intensity.

These drawbacks would be too high a price to pay for the one advantage of the asynchronous generator, namely the elimination of oscillations with variations in wind intensity. Asynchronous generators must therefore be rejected for large wind power plants.

Summary

It is quite feasible to have a synchronous generator driven by wind power running at constant revolutions directly in a governing network.

The damping of the transient caused by a change in wind speed is influenced by the behavior of the characteristic curve of the fan-wheel. It is strengthened when the operating point lies to the right of the so-called pullout point, and weakened when the operating point lies to the left of the pullout point. /392
Numerically, the influence is small; the oscillation will never be reinforced.

To avoid overloading the generator, and having the generator fall out of synchronization, a swiftly acting mechanical regulation of power is necessary. Only the proven method of shifting the vanes comes into consideration for this purpose. Lateral "turning out of the wind" and tipping the wind wheel or wheels must be rejected as completely unworkable from the electrical standpoint.

In designing the fan-wheel, the operating behavior of the synchronous generator must be taken into account, even if this costs something in "efficiency." The same is true for the choice of the number of vanes, where the danger of resonance with the natural oscillation must be avoided.

Asynchronous generators do not present any crucial advantages over synchronous generators, but instead have substantial drawbacks.

In order to calculate in advance the transient process, the designer of the generator must have the following data:

1. Wind intensity conditions, particularly events during a rise in wind intensity.

2. The time required for shifting the vanes.

3. Fan-wheel characteristic curves for various angles of inclination.